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PREDICTING THE AVERAGE ABSORPTANCE DURING THE CONTINUOUS WAVE L--ETC(U)

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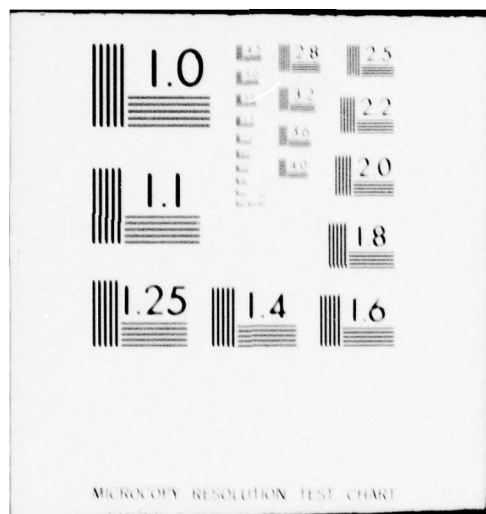
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PREDICTING THE AVERAGE ABSORPTANCE DURING
THE CONTINUOUS WAVE LASER PENETRATION OF
PAINTED ALLOYS.

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Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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William T. Laughlin

WILLIAM T. LAUGHLIN
Project Officer

Hector Rede

HECTOR REDE
Major, USAF
Chief, Effects & Vulnerability Branch

FOR THE COMMANDER

Louis H. Bernasconi

LOUIS H. BERNASCONI
Colonel, USAF
Chief, LEAPS Division

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (UNCLASSIFIED ABSTRACT) The average surface absorptance for the penetration of painted metal targets by a continuous wave laser is derived theoretically based on the assumption that the paint is thermally thick and is removed by a steady-state vaporization process. The heat required to melt through a painted metal target is postulated to enter the target during two phases: (1) Heat is conducted into the metal while the paint is being vaporized at steady-state from its surface; (2) After paint removal, heat is added to metal until melt-through by the laser radiation.		

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impinging on the resulting unpainted metal surface. A heat balance on the paint and metal plate permits the definition of an average surface absorptance for the entire melt-through event. This average absorptance is shown to be a function of the laser beam intensity, paint and metal thicknesses and the thermal properties of both paint and metal. The predicted importance of these variables is discussed, and the calculated absorptances compared with available absorptance data from actual melt-through experiments.

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SECTION I

INTRODUCTION

1. OBSERVATIONS OF EXPERIMENTAL DATA

Experimental results from the continuous wave (cw) laser melt-through of painted metal targets done by the Air Force Weapons Laboratory (AFWL), Naval Research Laboratory, et al., show an increase in the amount of energy required to penetrate painted metal plates as the intensity of the incident cw laser radiation increases (refs. 1 and 2). This is equivalent to a decrease in average fraction of laser energy absorbed with increasing laser beam intensity. The AFWL data from the irradiation of painted metal targets by a repetitively pulsed laser yielded absorptances no different than that obtained on unpainted metals.

These experimental results taken together tell nothing about the time history of the surface absorptance during the laser melt-through of painted metals. However, they are conclusive evidence of a change in the mechanism of paint removal from metal targets by laser radiation in the range of 1 to 100 kW/cm² of intensity. At intensities on the order of a kW/cm² or less the paint apparently decomposes and chars, and the surface of the metal retains a sufficient amount of decomposition products to keep the absorptance at the 50 to 90 percent level averaged through the melt-through time of the metal. At intensities above 10 kW/cm² average absorptance for melt-through appears to be approaching unpainted target values. These lower absorptance values indicate that either the paint removal process is absorbing more of the laser energy or more energy is being reflected because fewer decomposition products remain on the metal surface after the paint is removed.

One additional observation that can be made about the data is that the decrease in average absorptance towards unpainted metal values appears to occur at lower intensities for poorer thermal conducting alloys such as titanium and stainless steel than for alloys of aluminum. This suggests that the alloy's ability to

1. Laughlin, W. T., "Effect of Laser Beam Intensity and Sample Thickness of the Penetration of Painted Alloys," Proceedings of the Second DOD Laser Effects/Hardening Conference, NASA Ames Research Center, Moffett AFB, Calif., July 1975.
2. Towle, L., "Penetration Energies at 10.6 Microns," Appendix C.1, NRL High Energy Laser Program Progress Report, Jan-Jun 76, NRL Memo Rprt 3460 (in pub.).

remove heat from the paint-metal interface may influence the intensity at which the change in paint removal mechanism occurs, and the resulting change in average absorptance for a melt-through event.

2. EXISTING MODEL FOR PAINT BEHAVIOR

Previous studies on the behavior of heated paints have generally dealt with much slower heating rates than those obtained with laser radiation. Thermal properties and decomposition reactions are poorly understood for the conditions of paint irradiation of interest here. Only one analytical work has been proposed to describe paint behavior at an intensity on the order of a kW/cm^2 (ref. 3). This laser paint pyrolysis model was designed to describe the reradiation expected from the laser irradiated paint surface, not the absorption of a painted target. It predicts a char layer thickness, paint burning rate, and char surface temperature. The absorption of the charring paint is assumed to be unity, and complete removal of the paint is prevented by the assumption of a fixed cold wall metal temperature at the paint metal interface. This latter assumption appears to preclude the possibility of using this paint pyrolysis model as a starting point for predicting the average absorptance for complete melt-through of a metal plate.

A shift of emphasis to thinking about how paint removal might occur at higher intensities, leads to the idea that the paint might simply be vaporized from the target surface. This process might have some effective heat of vaporization, really a balance between actual heat of vaporization and heat that would be released from the limited amount of decomposition permitted at these high intensities. The following is an analytical derivation of the amount of heat left in a substrate metal plate and the resulting average absorptance through penetration of that plate, based on an assumed steady-state vaporization of its thermally thick paint layer.

3. Otto, R. G., et al., "Dual-Spot Tracking Study; Signature and Classical Effects," LMSC-L023776, Lockheed Laboratory, Palo Alto, Calif., February 1976.

SECTION II

THEORETICAL MODEL

1. BASIC ASSUMPTIONS

The heat required to melt through a painted metal target is postulated to enter the target during two phases: Phase (1)—Heat is conducted into the metal plate while the paint is being vaporized from its surface. Phase (2)—Heat is added to the metal by the laser radiation impinging on the unpainted metal surface from the instant the paint has been removed until the time of plate melt-through.

During Phase (1), the intensity of the laser radiation must be sufficiently high, and the paint sufficiently thick and nonconductive in order that the paint layer is thermally thick. Also, the surface of the metal during Phase (2) must be enough like an ordinary unpainted alloy surface to be represented by the same average absorptance through the melting point as an unpainted alloy.

Paints typically have an optical absorptance of greater than 0.5 at laser wavelengths, and a thickness of 1 to 10 mils depending upon the number of coats. The time to vaporize a layer of paint, t_v , is proportional to its heat of vaporization, $(H_v)_p$, density, ρ_p , and thickness, ℓ_p . The t_v is inversely proportional to the absorbed laser intensity, $\alpha_p I$.

$$t_v \sim \frac{(\rho H_v)_p \ell_p}{\alpha_p I} \quad (1)$$

The subscript p denotes parameters of the paint.

If the heat of vaporization is on the order of 1000 j/gm and the density about 1.5 g/cm³, then for an absorbed intensity of 10 kW/cm², the time to completely remove 10 mils of paint is approximately 4 msec (ref. 3 and appendix).

The time for heat to flow through 10 mils of paint (a material with a thermal diffusivity κ_p of about 0.002 cm²/sec) is given by

$$t \sim \frac{\ell^2}{\kappa_p} \quad (2)$$

which is approximately 300 msec. Even allowing for some error in the estimated thermal properties, paint is clearly thermally thick at intensities of a kW/cm² and greater.

2. TEMPERATURE HISTORY OF PAINT LAYER

Because the paint is thermally thick, the transfer of heat into the metal plate will occur relatively late in the removal process. To determine the approximate temperature boundary condition for the metal plate while the paint is vaporizing, we first observe that the temperature profile behind a steadily receding surface is exponential in form

$$T = T_v \exp \left[- A (x - v_s t) \right] \quad (3)$$

where T_v is the surface vaporization temperature, v_s is the velocity of surface recession, x represents position within the paint layer (at front surface $x = 0$), and t is time, the value of A determines the depth of penetration of heat behind the receding surface in cm⁻¹.

$$A = v_s / \kappa_p \quad (4)$$

$$v_s = \frac{\ell_p}{t_v} = \frac{\alpha_p I}{(\rho H_v)_p}$$

where κ_p is the thermal diffusivity, α_p is the absorptance, $(\rho H_v)_p$ is the volume heat of vaporization, and ℓ_p is the thickness of the paint, t_v is defined as the time for complete paint removal. Substituting these thermal properties of the paint, equation (3) becomes

$$T = (T_v)_p \exp \left[- \frac{\alpha_p I x}{(\rho H_v)_p \kappa_p} \right] \exp \left[\left(\frac{\alpha_p I}{(\rho H_v)_p} \right)^2 \frac{t}{\kappa_p} \right] \quad (5)$$

where $(T_v)_p$ is a vaporization temperature of the paint.

If the rear surface of the paint is in good thermal contact with metal, or has no thermal contact with its substrate, equation (5) will not provide the rear surface temperature history for the paint when substituting $x = \ell_p$, the paint thickness. Neither of these two extremes is correct, of course, the actual heat transfer conditions being somewhere in between. The form of equation (5) is

approximately correct, however, for a rapid exponential rise to some paint vaporization temperature. If the thermal contact of paint to metal were perfect, heat would be absorbed into the metal and the rear paint surface would approach vaporization more slowly than suggested by equation (5). On the other hand, a less perfect thermal contact to the metal might permit the rear surface paint temperature to rise more rapidly than shown here. Solving for the correct temperature boundary condition for the front surface of the metal plate would be an extremely complex problem. Considering the fact that even an exact solution might not correctly represent the temperature history because of very poorly known thermal properties, it may be just as well to assume that the simple exponential rise of equation (5) is a fair representation of the kind of temperature rise expected on the metal surface.

3. PLATE HEATING WITH EXPONENTIAL TEMPERATURE AT BOUNDARY

A transient solution for the temperature history of a finite thickness plate, with constant thermal properties, rear surface insulated, zero initial temperature and surface temperature, $V \exp(at)$ at $t > 0$, is readily available in Carslaw and Jaeger (ref. 4).

$$v = V \exp(at) \frac{\cosh\left[\left(a/\kappa_m\right)^{1/2} x\right]}{\cosh\left[\left(a/\kappa_m\right)^{1/2} \ell_m\right]} - \frac{4V}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n \exp\left(-\kappa_m (2n+1)^2 \pi^2 t / 4\ell_m^2\right)}{(2n+1) \left[1 + 4a\ell_m^2 / (2n+1)^2 \pi^2 \kappa_m\right]} \cdot \cos\left[\frac{(2n+1)\pi x}{2\ell_m}\right] \quad (6)$$

The subscript m is used to distinguish parameters belonging to metal.

With $x = \ell_p$ the rear surface of the paint, equation (5) is identical in form to the $V \exp(at)$ surface boundary condition. Using the constants of equation (5) for V and a , and defining $v = \alpha_p I / (\rho H_V)_p (\kappa_p \kappa_m)^{1/2}$ and $N = (2n+1) \pi / 2\ell_m$, the expression for temperature as a function of position and time in the metal plate becomes

$$T = (T_V)_p \exp\left(-\frac{\alpha_p I \ell_p}{(\rho H_V)_p \kappa_p}\right) \left[\exp(\kappa_m v^2 t) \frac{\cosh\left(\frac{vx}{v\ell_m}\right)}{\cosh\left(\frac{v\ell_m}{v\ell_m}\right)} - \frac{2}{\ell_m} \sum_{n=0}^{\infty} \frac{(-1)^n \exp\left(-\kappa_m N^2 t\right)}{N \left(1 + v^2 / N^2\right)} \cdot \cos Nx \right] \quad (7)$$

4. Carslaw, H.S. and J.C. Jaeger, Conduction of Heat in Solids, Oxford University Press, London, England, 1959.

4. HEAT IN METAL UPON COMPLETE PAINT REMOVAL

Substituting $t = t_v$ in equation (7), multiplying by the density and heat capacity of the metal, $(\rho C_p)_m$, and integrating over the metal thickness, ℓ_m , gives the amount of heat contained in the metal plate after the paint is removed, $Q(t_v)$, in j/cm^2 .

$$Q(t_v) = (\rho C_p)_m (T_v)_p \left[\frac{\tanh(v \ell_m)}{v} - \frac{2}{\ell_m} \sum_{n=0}^{\infty} \frac{\exp[-\kappa_m(v^2 + N^2) t_v]}{v^2 + N^2} \right] \quad (8)$$

where

$$\begin{aligned} t_v &= (\rho H_v)_p \ell_p / \alpha_p I \\ v &= \alpha_p I / (\rho H_v)_p (\kappa_m \kappa_p)^{1/2} \\ N &= (2n + 1) \pi / 2 \ell_m \end{aligned}$$

5. CALCULATION OF AVERAGE ABSORPTANCE

The addition of heat in the metal from phase (1) and that from (2) must equal the heat required to melt through the metal plate. Writing this in the form of a heat balance for metal only

$$Q(t_v) + \alpha_m I (t_m - t_v) = Q_m \ell_m \quad (9)$$

α_m is the absorptance of the metal surface after the paint has vaporized, t_m is the metal melt-through time, and Q_m is the total heat capacity of the metal upon penetration. The Q_m may include all or some fraction of the heat of fusion if strong aerodynamic forces are present.

The heat required to vaporize the paint plus the heat required to melt the metal must also equal the total absorbed laser energy. By writing this as a heat balance on paint and metal, an average or overall absorptance for penetration of a painted metal plate can be defined

$$Q_m \ell_m + (\rho H_v)_p \ell_p = \alpha_{\text{avg}} I t_m \quad (10)$$

Remembering that $t_v = (\rho H_v)_p \ell_p / \alpha_p I$ and combining equations (9) and (10) the following expression for α_{avg} results

$$\alpha_{\text{avg}} = \frac{\alpha_m (Q_m \ell_m + (\rho H_v)_p \ell_p)}{Q_m \ell_m + (\rho H_v)_p \ell_p \alpha_m / \alpha_p - Q(t_v)} \quad (11)$$

Using equation (8), the expression for the heat remaining in the metal after paint removal, a final equation is obtained with α_{avg} as a function of laser beam intensity, paint and metal thicknesses and thermal properties

$$\alpha_{avg} = \frac{\alpha_m (Q_m \ell_m + (\rho H_v)_p \ell_p)}{Q_m \ell_m + (\rho H_v)_p \ell_p \alpha_m / \alpha_p} \quad (12)$$

$$- (\rho C_p)_m (T_v)_p \left[\frac{\tanh(v \ell_m)}{v} - \frac{2}{\ell_m} \sum_{n=0}^{\infty} \frac{\exp[-\kappa_m (v^2 + N^2) t_v]}{v^2 + N^2} \right]$$

where

$$t_v = (\rho H_v)_p \ell_p / \alpha_p I$$

$$v = \alpha_p I / (\rho H_v)_p (\kappa_m \kappa_p)^{1/2}$$

$$N = (2n + 1)\pi / 2\ell$$

SECTION III

DISCUSSION

1. LIMITS BECAUSE OF ASSUMPTIONS

Equation (12) is a function which defines a direct although apparently complex dependence of the average absorptance for a melt-through event on laser beam intensity. Because of the assumptions of (1) steady-state paint vaporization and (2) a single exponential rise in temperature at the metal surface as the driving force for transferring heat into the metal, the predicted α_{avg} is expected to be most accurate at high intensities or where α_{avg} is very near α_m . Even though at lower intensities the calculated magnitude of α_{avg} is relatively uncertain, equation (12) should be very useful to define the intensity where significant decreases occur in α_{avg} toward unpainted metal values.

Figure 1 shows a prediction of the average absorptance of 0.0406 cm thick painted 2024 aluminum versus intensity based on the paint properties of table 1.

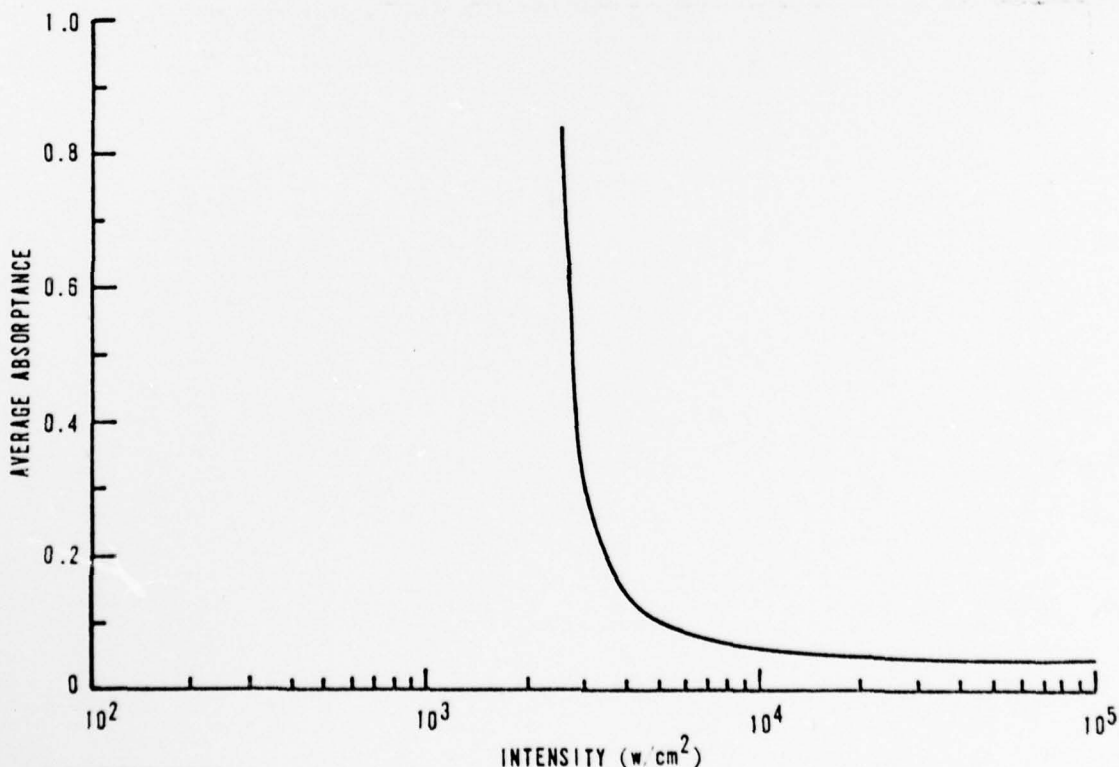


Figure 1. Predicted Average Absorptance of Painted 2024 Aluminum

Table 1
PROPERTIES OF A TYPICAL PAINT

Absorptance, α_p	0.80
Thickness, ℓ_p	0.025 cm
Volume Heat of Vaporization $(\rho H_v)_p$	2000 j/cm ³
Vaporization Temperature, $(T_v)_p$	1000°C
Thermal Diffusivity, κ_p	0.002 cm ² /sec

Metal properties used are listed in table 2. Corresponding predictions of average absorptance versus intensity for painted 6Al4V titanium and 304 stainless steel are given in figures 2 and 3. Both figures show an increase in the expected average absorptance as the intensity decreases, the change for aluminum occurring very rapidly with a large increase of absorptance. (Impossible values of $\alpha_{avg} > 1$ can be predicted with further decrease in intensity.) The increases predicted for titanium and stainless steel are much more modest, leveling off at an absorptance of about 0.5 and 0.3, respectively.

Table 2
PROPERTIES OF METAL ALLOYS
(Averaged from Room Temperature to Melt)

Metal Property	2024 Aluminum	6Al4V Titanium	304 Stainless Steel
Enthalpy for melt-through, Q_m (halfway between solidus and liquidus temps) (j/cm ³)	2184	5164	5647
Volume heat capacity $(\rho C_p)_m$ (j/cm ³ °C)	3.05	2.45	3.23
Thermal Diffusivity, κ_m (cm ² /sec)	0.56	0.037	0.046
Unpainted metal absorptance, α_m	0.03	0.25	0.12

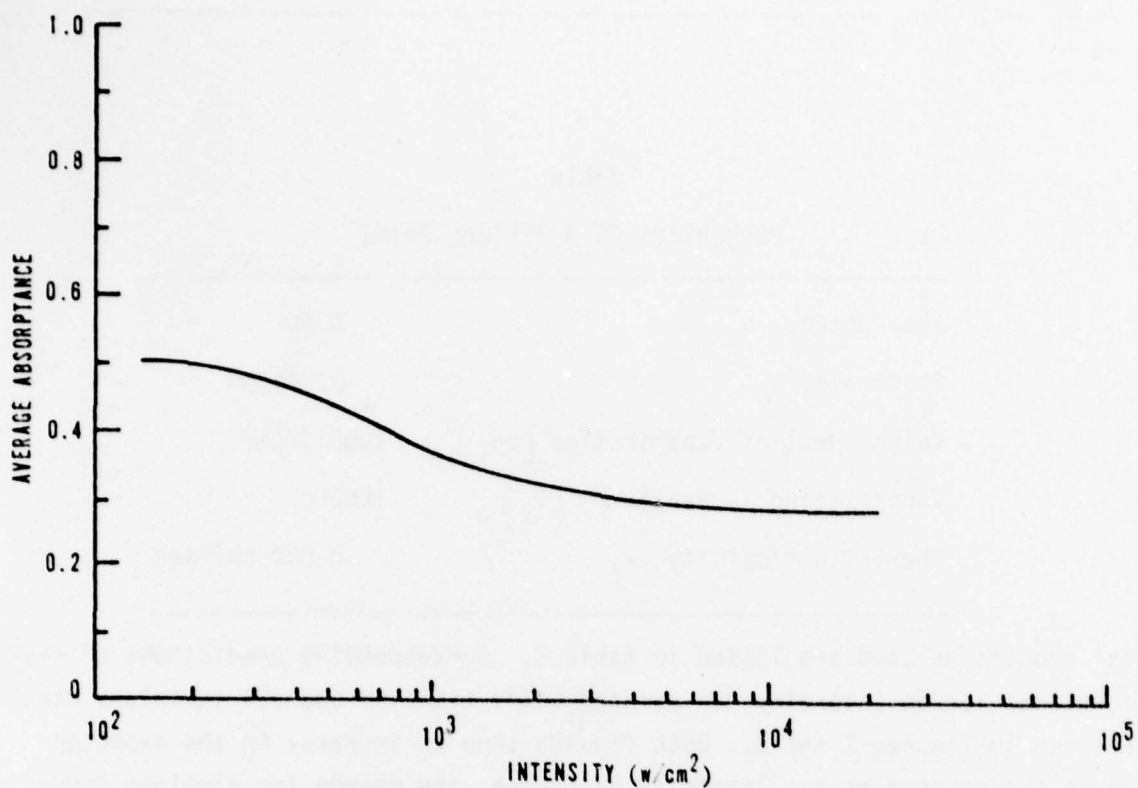


Figure 2. Predicted Average Absorptance of Painted 6Al4V Titanium

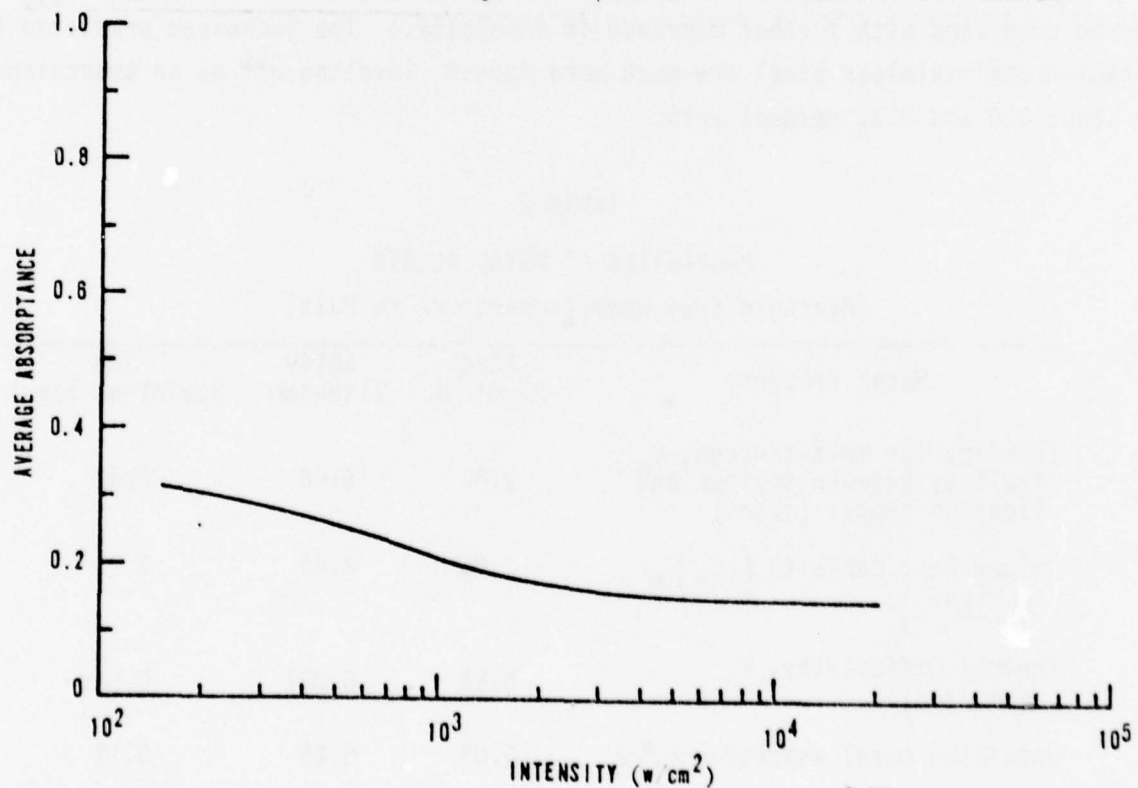


Figure 3. Predicted Average Absorptance of Painted 304 Stainless Steel

This very different behavior for alloys of high and low thermal diffusivity is caused by differences in magnitude of the term in brackets in the denominator of equation (12). The amount of heat that can be absorbed by aluminum, the higher diffusivity alloy is predicted to be much greater than that for the other alloys. This is the reasonable result, although remembering the assumptions behind equation (12) these magnitudes of absorbed heat are only approximate, particularly as the intensity falls below a few kW/cm^2 .

2. SENSITIVITY TO METAL PARAMETERS

a. Metal Thermal Diffusivity

Comparing figures 1, 2 and 3 (looking at the intensities at which absorptance increases occur with decreasing laser intensities) reveals a predicted absorptance increase for the aluminum alloy at somewhat higher intensity than that shown by the titanium and stainless steel alloys. Quantitatively describing the importance of the substrate metal to the prediction of absorptance increases can perhaps best be done by plotting values of intensity for significant absorption increases against the metal thermal diffusivity. This is done in three possible ways in figure 4; 5, 10 and 50 percent of the difference between high and low intensity values of absorptance, assuming a maximum of 0.9 for 2024 aluminum. The three different ways of defining the absorptance change result in rather low slopes of varying values. The importance of metal thermal diffusivity is, therefore, approximately a square root dependence or less. This vaporizing paint model says then that the higher diffusivity alloys should display an absorptance change with intensity at only slightly higher intensities than the less conductive alloys.

b. Metal Surface Absorptance

In the derivation, it was assumed that after the paint is removed the surface of the metal has the same absorptance as an unpainted alloy. Suppose now that some small amount of paint or prepaint surface treatment residues are left on the surface. The metal absorptance should certainly be increased, particularly for aluminum alloys. Average absorptance should then also increase. Figures 5 and 6 show the average absorptance versus intensity for a variety of metal absorptance values for 2024 aluminum and 6Al4V titanium, respectively. For both alloys, the average absorption increases about the same amount at all intensities with increased metal absorptance after paint removal.

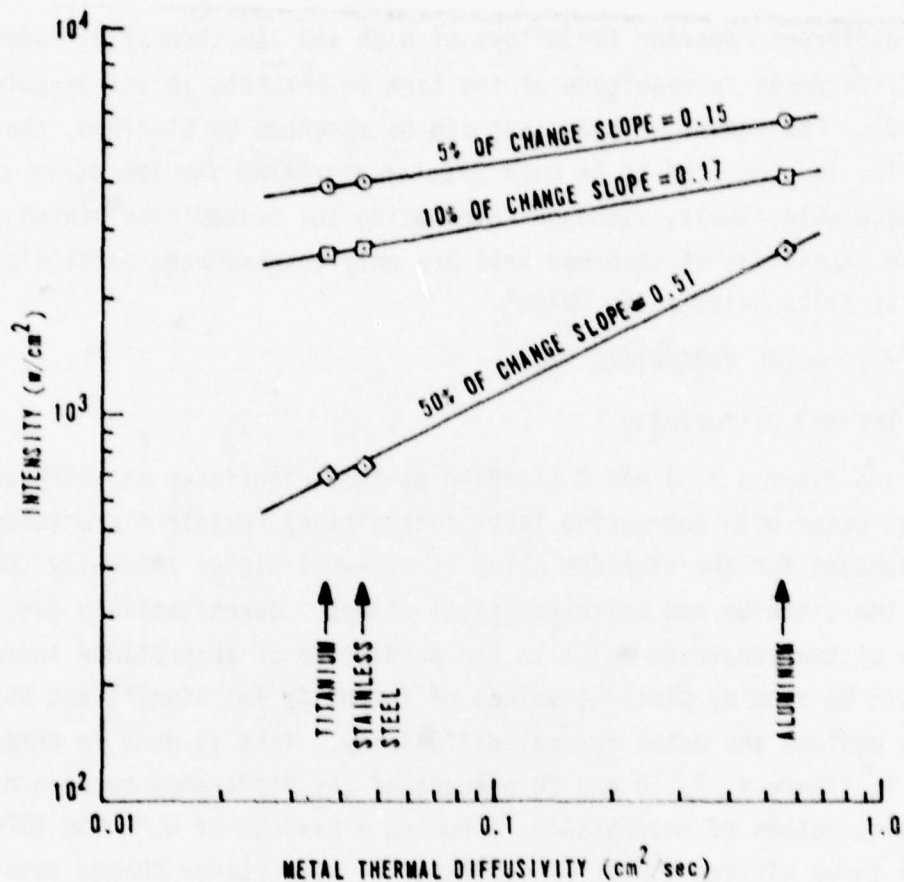


Figure 4. Intensity for Average Absorption Change vs. Metal Diffusivity

c. Metal Thickness

An additional parameter that should influence the amount of heat absorbed by a metal plate while the paint is being vaporized is the thickness of the metal itself. The greater the metal thickness, the more heat must be deposited by the vaporizing paint for it to make a significant increase in the overall average absorptance. That is equivalent to saying that average absorptance should undergo its change at lower intensities for thicker samples. Figures 7 and 8 show that this is true for both an alloy of high and low thermal conductivity. Figure 9 is a plot of the intensity for average absorptance change (50 percent point) versus metal thickness. Both alloys show a slope of approximately -1, indicating that the intensity for average absorptance change is inversely proportional to metal thickness.

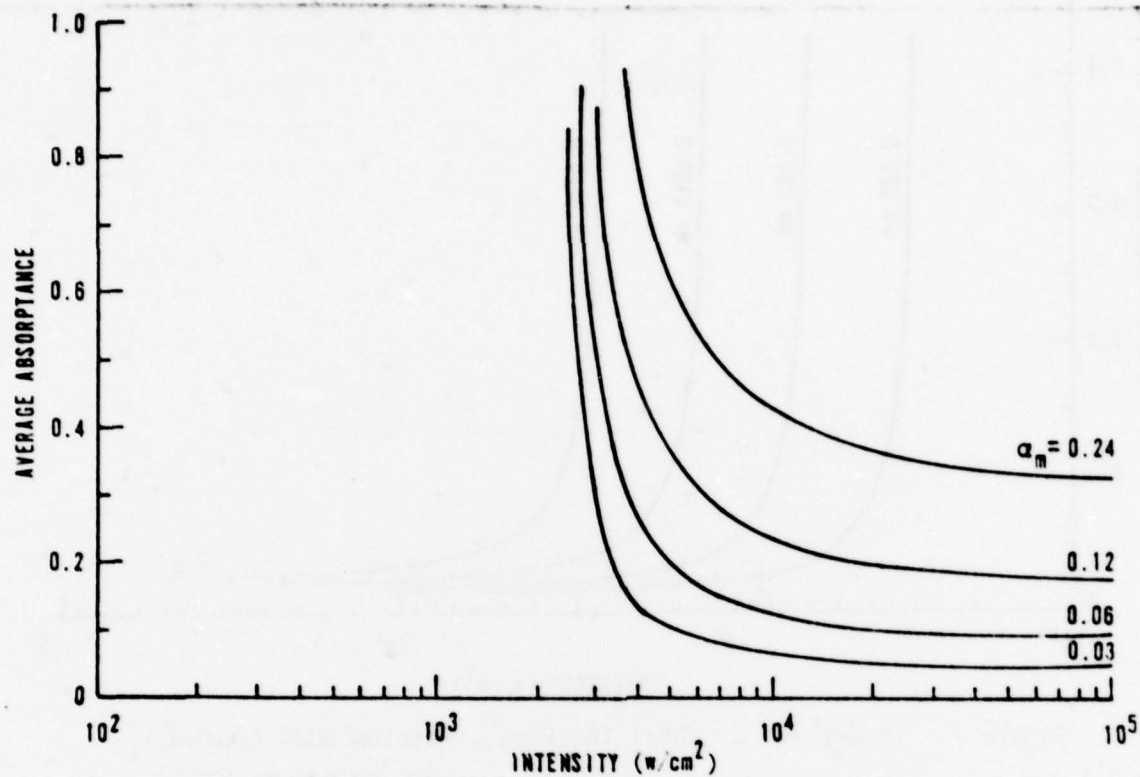


Figure 5. Importance of Metal Absorptance: Painted 2024 Aluminum

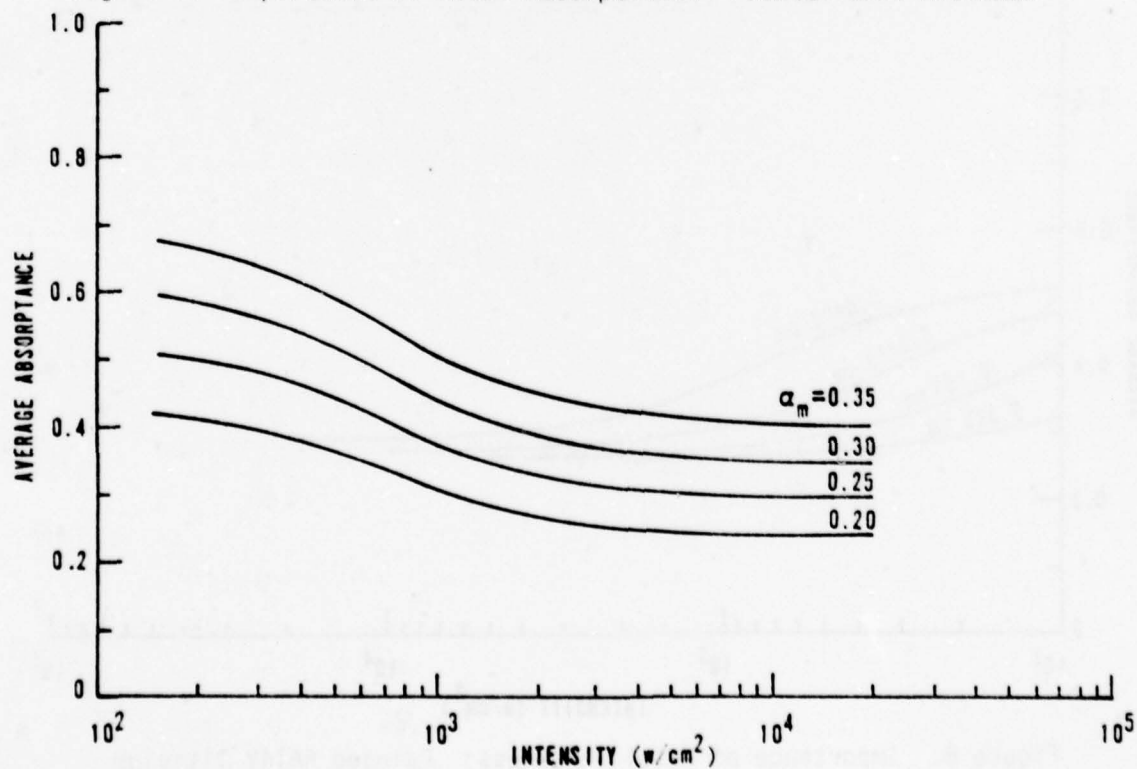


Figure 6. Importance of Metal Absorptance: Painted 6A14V Titanium

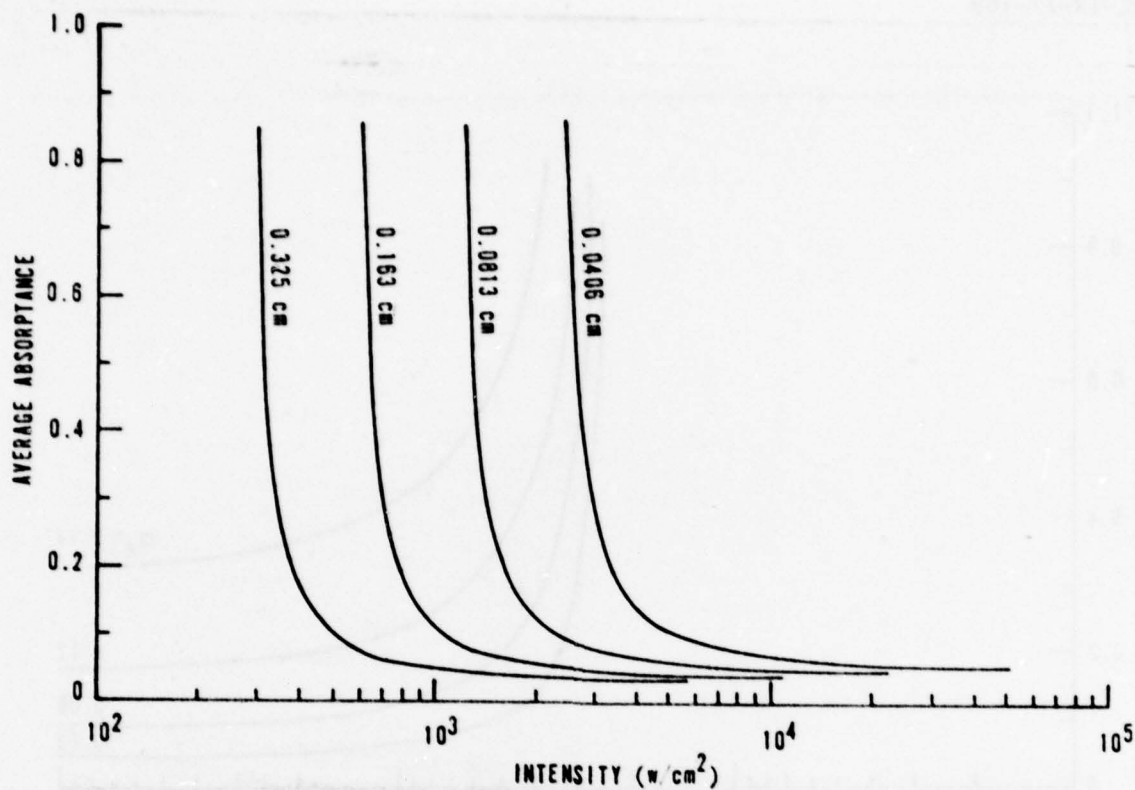


Figure 7. Importance of Metal Thickness: Painted 2024 Aluminum

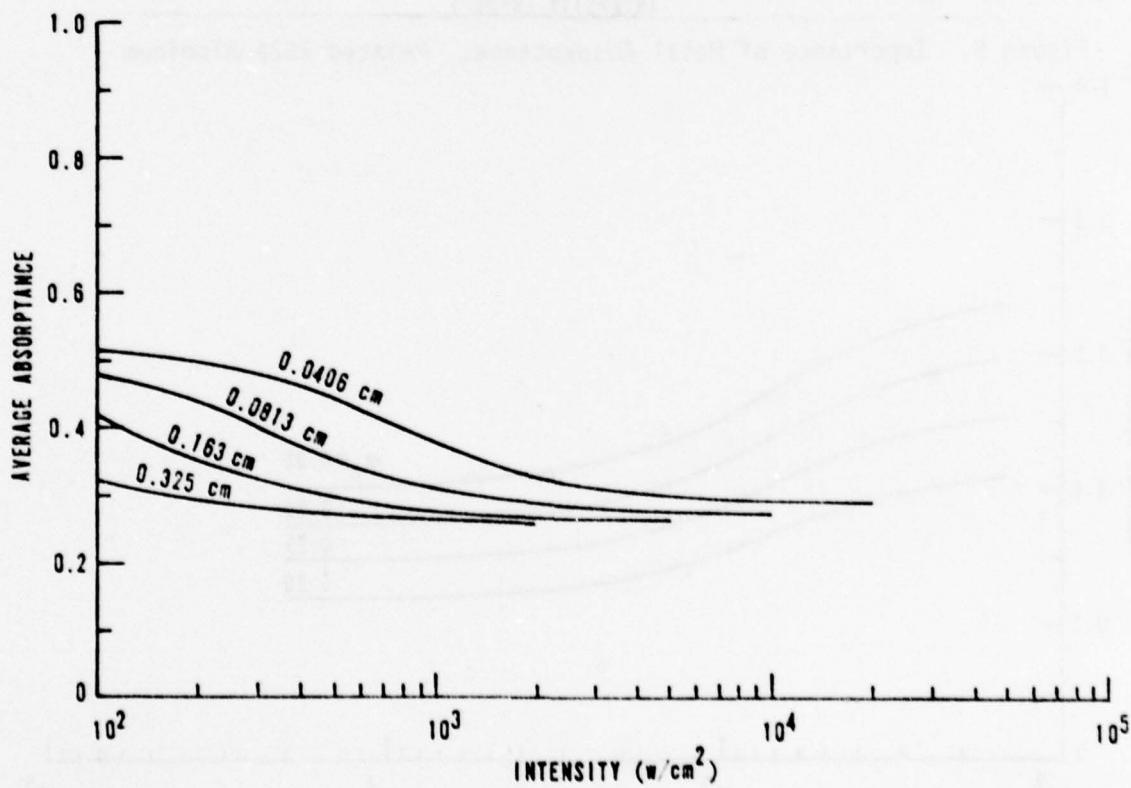


Figure 8. Importance of Metal Thickness: Painted 6A14V Titanium

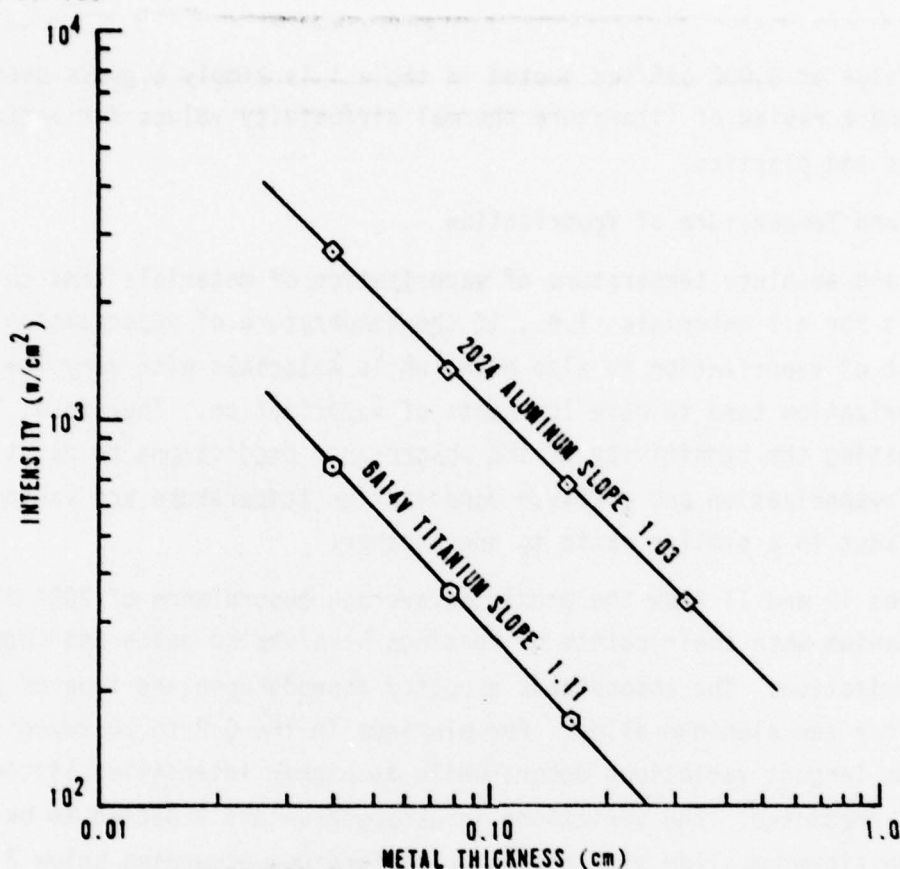


Figure 9. Intensity for Average Absorptance Change vs. Metal Thickness

3. SENSITIVITY TO PAINT PARAMETERS

The thermal properties of paints are rather poorly known, and probably vary considerably from one kind of paint to another. Paints are typically a varied mixture of several types of inorganic pigment suspended in several kinds of organic resins or binders. They do not vaporize at a single temperature or have a corresponding single value for heat of vaporization. However, in order to derive the expression for predicting absorptance as given by equation (12), single values of temperature and heat of vaporization were assumed. It is necessary then to locate some kind of average values of these properties for substitution into equation (12). Varying these values will then permit an evaluation of the sensitivity of the average absorptance predictions to the paint properties and, hence, the importance of obtaining and using accurate paint property values for paints found on actual targets.

The heat of vaporization of paint quoted in table 1 was measured experimentally by AFWL (see appendix). Radiometer measurements of temperature by AFWL on painted metal targets being penetrated by a 10.6 micron laser show temperatures that range from 500° to 1500°C. A middle value of 1000°C was chosen in table 1. The thermal

diffusivity value of $0.002 \text{ cm}^2/\text{sec}$ quoted in table 1 is simply a guess based on reference 3 and a review of literature thermal diffusivity values for various organic resins and plastics.

a. Heat and Temperature of Vaporization

Heat and absolute temperature of vaporization of materials tend to be in the same ratio for all materials; i.e., if the temperature of vaporization is high, the heat of vaporization is also high, while materials with very low temperatures of vaporization tend to have low heats of vaporization. Therefore, in the process of testing the sensitivity of the absorptance predictions to paint properties, heat of vaporization and absolute vaporization temperature are varied together and kept in a similar ratio to one another.

Figures 10 and 11 show the predicted average absorptance of 2024 aluminum and 6A14V titanium when their paints or coatings have varied heats and temperatures of vaporization. The absorptance expected depends upon the type of paint, particularly for the aluminum alloy. For aluminum in the 0.2 to 20 kW/cm^2 intensity range the largest variations occur, while at higher intensities little difference is predicted. The variations in absorptance are expected to be less severe for the titanium alloy with the major differences occurring below 2 kW/cm^2 intensity. Again, at high intensities average absorptance should be similar for different types of paint.

This vaporization of paint model postulates the existence of certain combinations of alloy type, and laser intensities that will cause some paints to be clean burning and others highly absorptive at the same intensity. Of course, in this derivation the paints were all assumed to absorb 80 percent of the laser energy, but great differences in the average absorptance for the entire melt-through of a painted metal plate still result under certain conditions. This behavior depends primarily on how little heat the paint layer conducts into the substrate metal while the paint is vaporizing, and not the absorptance of the paint itself. The model also suggests that the concept of the clean burning paint only exists over certain ranges of laser intensity and that its effectiveness depends on the thermal properties and absorptance of the substrate metal, as well as the properties of the paint itself.

b. Paint Thermal Diffusivity

The thermal diffusivity of the paint is present in equation (12) only in the v term as the square root of the thermal diffusivity. Predicted absorptance

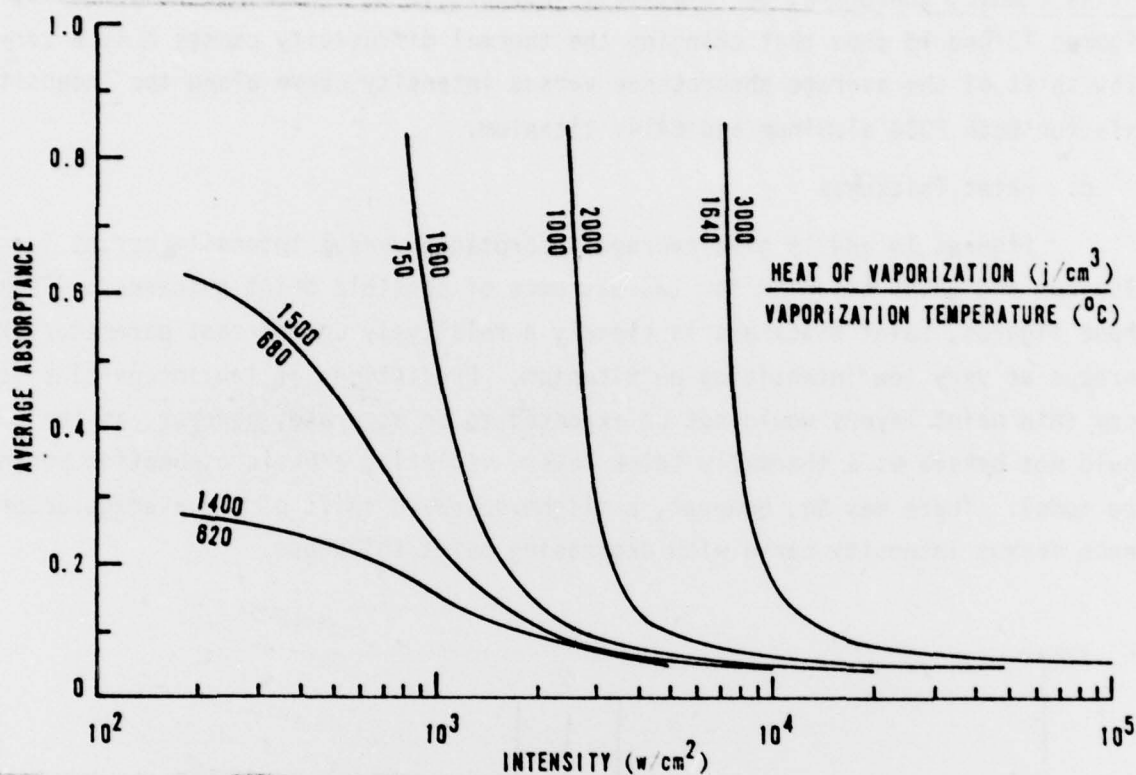


Figure 10. Importance of Temperature and Heat of Vaporization: 2024 Aluminum

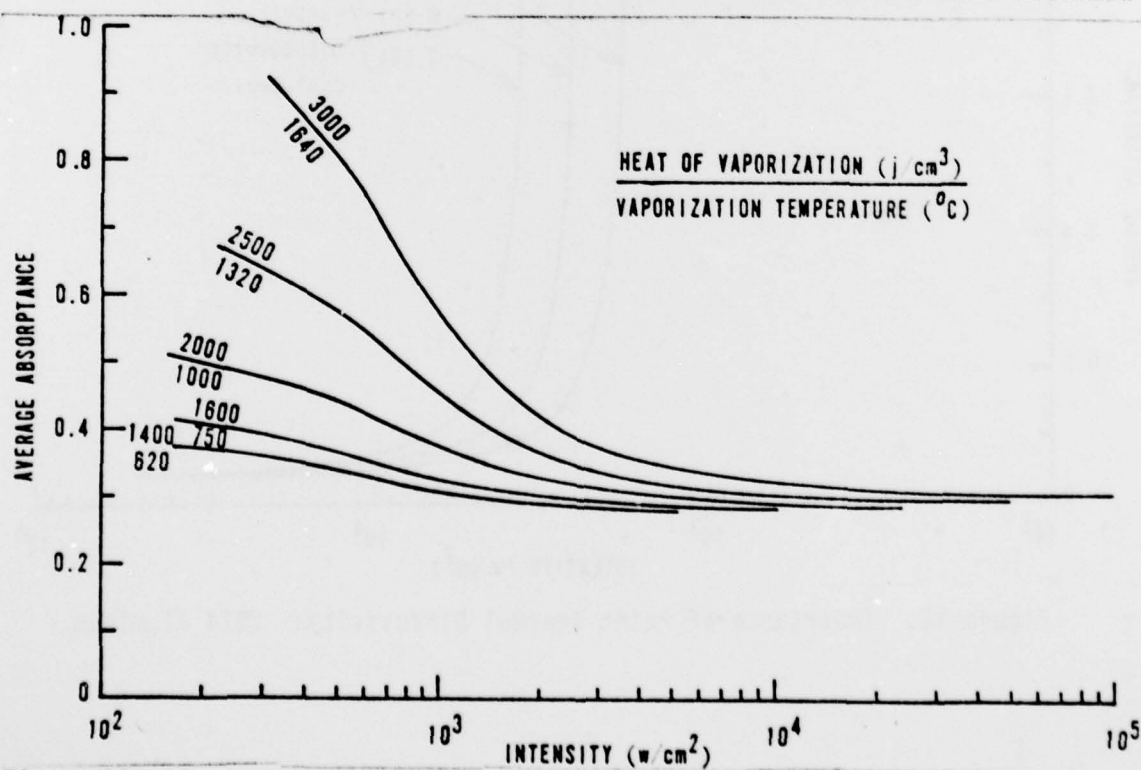


Figure 11. Importance of Temperature and Heat of Vaporization: 6Al4V Titanium

curves should, therefore, be relatively insensitive to the paints' diffusivity. Figures 12 and 13 show that changing the thermal diffusivity causes only a very slow shift of the average absorptance versus intensity curve along the intensity axis for both 2024 aluminum and 6Al4V titanium.

c. Paint Thickness

Figures 14 and 15 give average absorptance versus intensity curves for 2024 aluminum and 6Al4V titanium for two extremes of possible paint thickness. From these figures, paint thickness is clearly a relatively unimportant parameter except perhaps at very low intensities on titanium. Predictions at low intensities for very thin paint layers would not be expected to be accurate, however, as the paint could not behave as a thermally thick layer, violating a basic assumption behind the model. There may be, however, a slight downward shift of the average absorptance versus intensity curve with decreasing paint thickness.

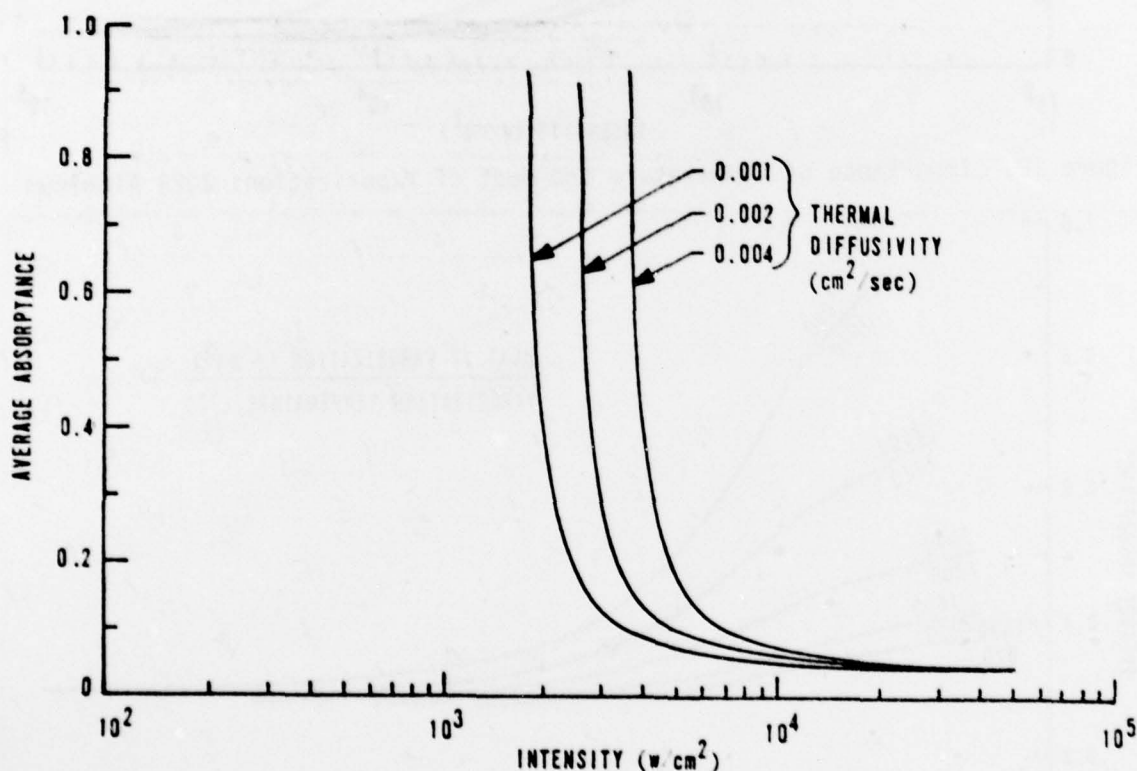


Figure 12. Importance of Paint Thermal Diffusivity: 2024 Aluminum

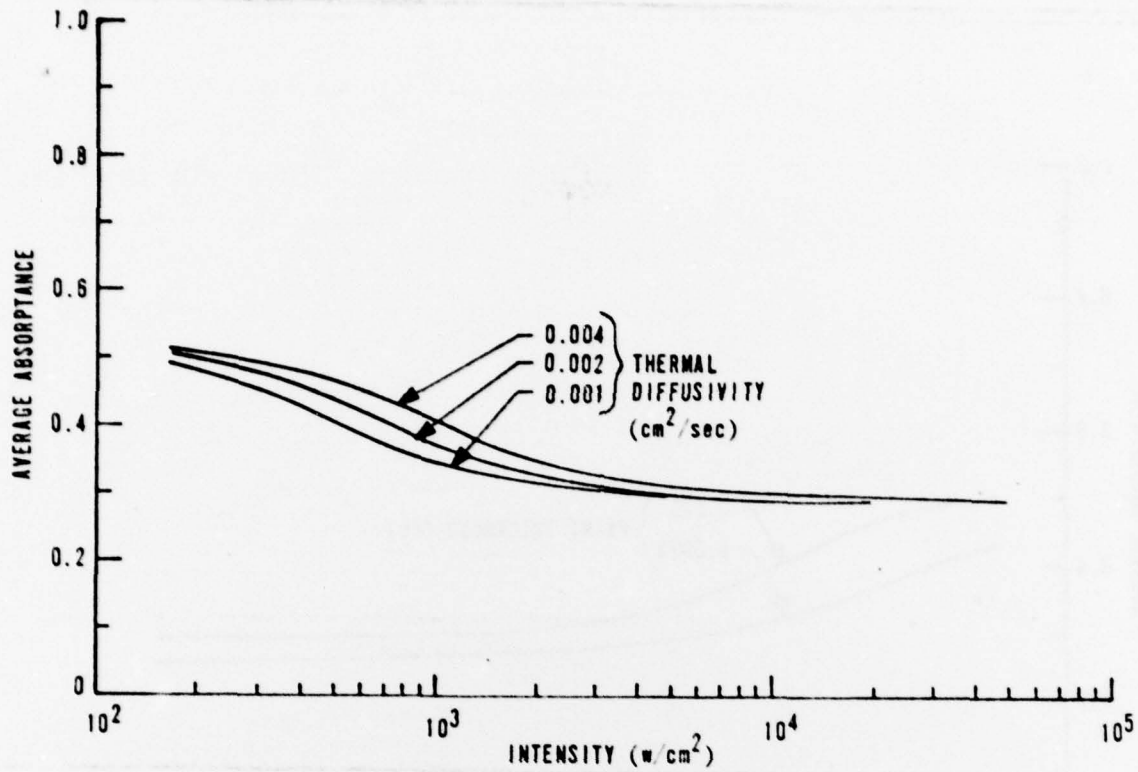


Figure 13. Importance of Paint Thermal Diffusivity: 6Al4V Titanium

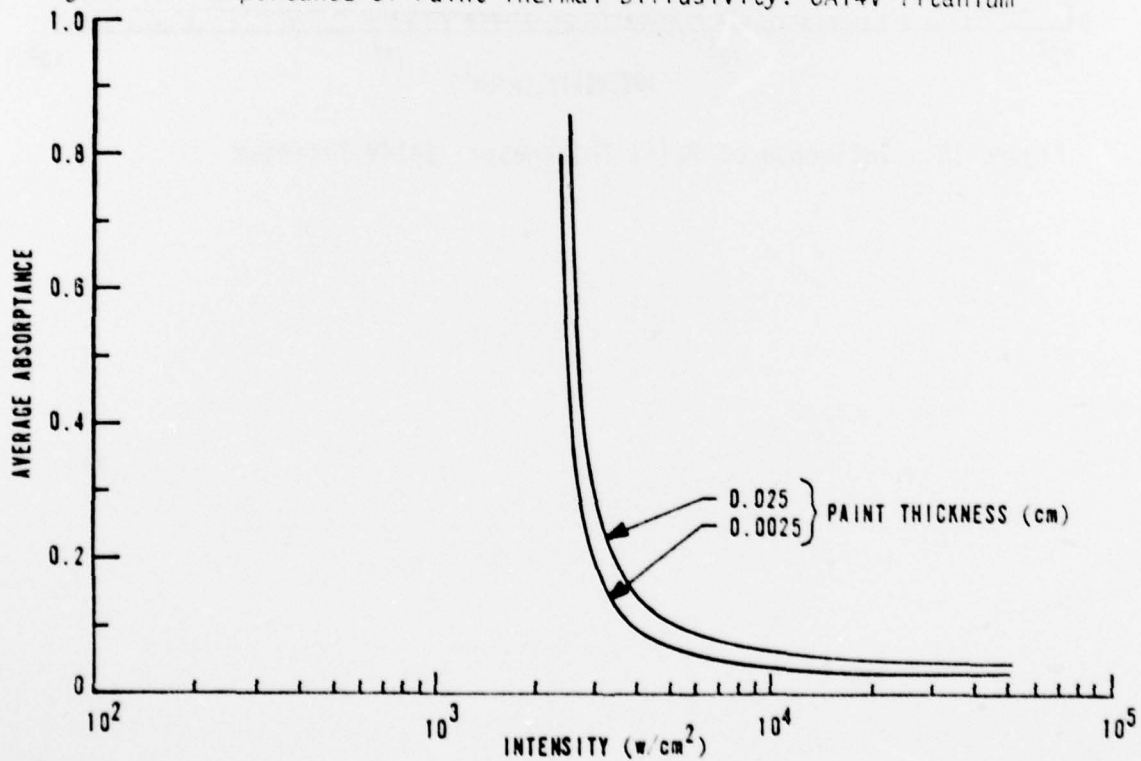


Figure 14. Influence of Paint Thickness: 2024 Aluminum

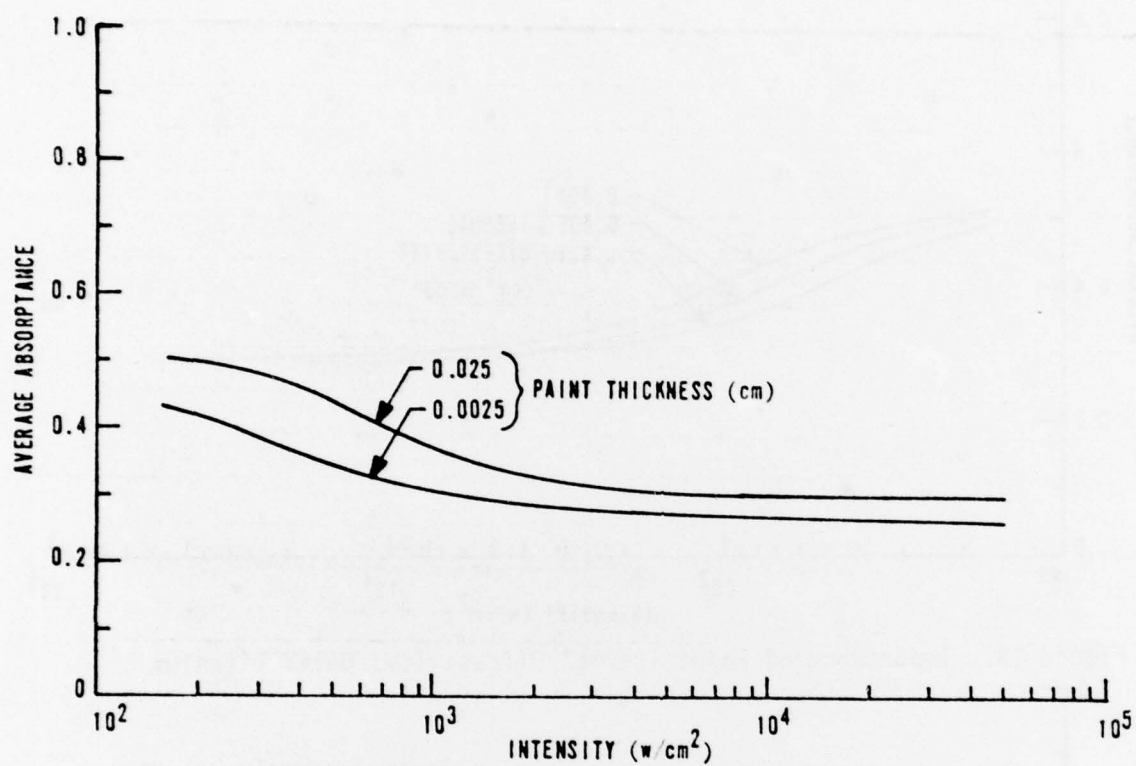


Figure 15. Influence of Paint Thickness: 6A14V Titanium

SECTION IV COMPARISON WITH DATA

1. INTENSITY DEPENDENCE OF ABSORPTANCE

a. AFWL Data

The most important test of the steady-state paint vaporization model is how well it can predict average absorptance for the actual melt-through by a laser of a painted metal plate, over a broad range of beam intensity. Figures 16, 17 and 18 show a collection of AFWL melt-through data for 2024 aluminum, 6Al4V titanium and 304 stainless steel metal plates, respectively. Three different kinds of paint coatings were used on these samples and are identified in the figures. The curves plotted in figures 16, 17 and 18 are not intended to fit the data points, but are predictions made independent of the data based on the input parameters for the paints and metals listed in tables 1 and 2 with changes or additions listed in table 3.

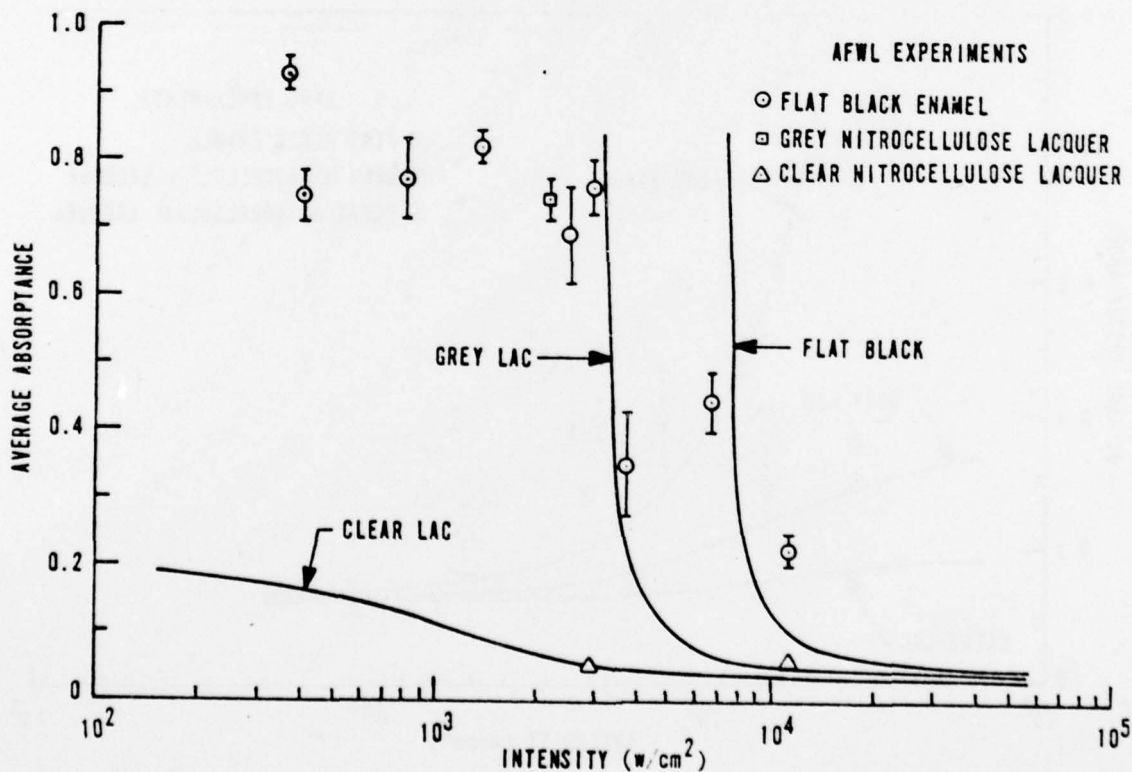


Figure 16. Absorptance Predictions with Melt-Through Data for Three Paints: 16 MIL 2024 Aluminum

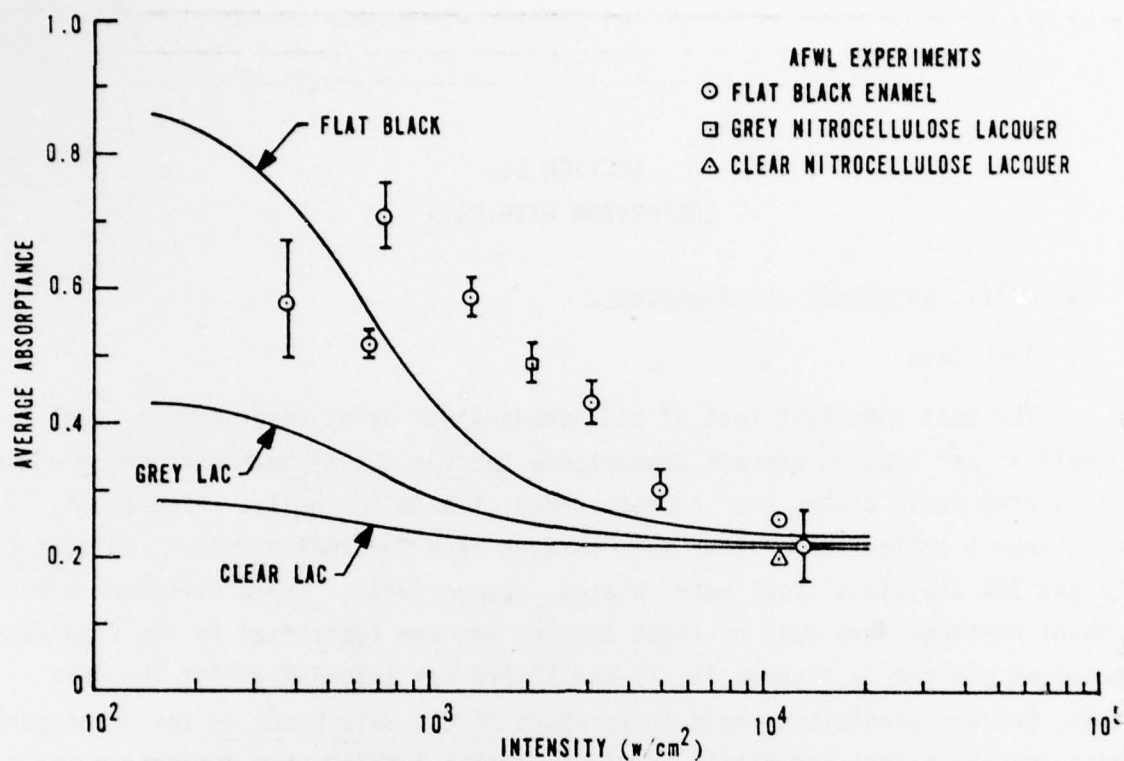


Figure 17. Absorbance Predictions with Melt-Through Data for Three Paints: 16 MIL 6A14V Titanium

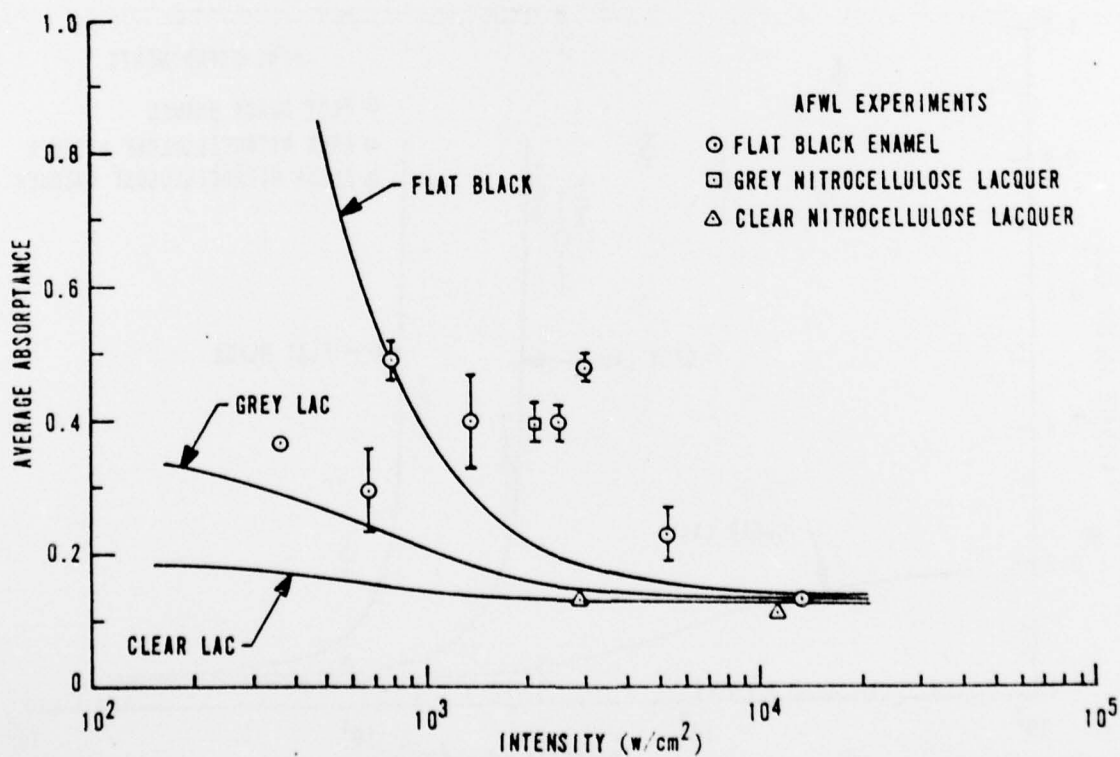


Figure 18. Absorbance Predictions with Melt-Through Data for Three Paints: 16 MIL 304 Stainless Steel

Table 3

PARAMETERS USED FOR AFWL DATA PREDICTIONS
(Figures 16, 17 and 18)

Metal

Thickness of Metal = 0.0406 cm

Assumed Absorptance of Metal Surface:

<u>Alloy</u>	<u>Absorptance</u>
2024 Aluminum	0.03
6A14V Titanium	0.20
304 Stainless Steel	0.12

Paint

Thickness of Paint = 0.010 cm

Heat and Temperature of Vaporization

<u>Paint</u>	<u>Heat of Vap(j/cm³)</u>	<u>Temp of Vap(°C)</u>
Clear Nitrocellulose Lacquer	1350*	590
Grey Nitrocellulose Lacquer	2150*	1100
Flat Black Enamel	3000	1640

*Measured experimentally: See appendix.

The paint vaporization model can predict fairly successfully, for a given kind of paint, the point on the intensity scale where significant changes in the average absorptance should occur. As expected from assumptions made during the derivation, however, the predicted absorptance values are not representative of actual data. Although these curves often do lie within the scatter of data points collected from several different experimental series, their slope is often too steep to represent data over the full range of intensities.

This paint removal model does predict additional phenomena: At high intensities it suggests that paints of all different heats and temperature of vaporization will show absorptance values for melt-through of similar magnitude. Absorptance data at intensities above 10^4 W/cm² in figures 17 and 18 on 6A14V titanium and 304 stainless steel confirm this prediction. At somewhat lower intensities, i.e.,

2 to 3 kW/cm², large differences in absorption are predicted between samples with the high and low heat of vaporization paints. Data in figures 16 and 18 on 2024 aluminum and 304 stainless steel confirm these large differences in average absorptance.

Thus, the paint removal by vaporization model explains melt-through data on painted targets by predicting intensities at which large changes in average absorptance are expected. The theory also suggests that the magnitude of the change is highly dependent on the kind of paint or coating applied to the metal surface.

b. Air Force Materials Laboratory (AFML) Data

Average absorptance values have been calculated from melt-through data taken by AVCO Lowell under an AFML surface skin coatings program. These absorptance data are plotted in figure 19 for both standard surface skin preparation and painting, and for the same metals painted with a cleanly degrading polymer (CDP) and top coat.

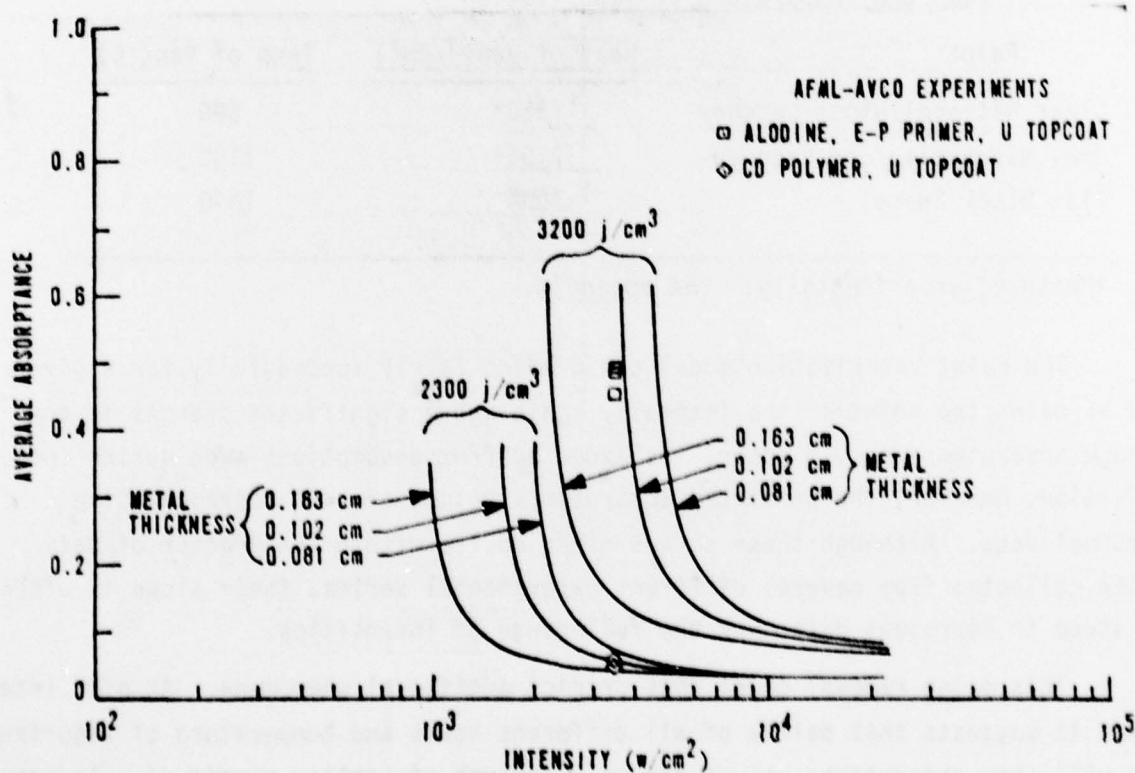


Figure 19. Absorptance Predictions and Melt-Through Data for Two Coatings 32, 40 and 64 MIL 2024 Aluminum

Since the heats of vaporization of these paints were not known, curves of average absorptance versus intensity predicted by the paint vaporization model were adjusted by varying the heat until the magnitude of the average surface absorptance most closely approximates the experimental data. A heat of vaporization of 3200 j/cm^3 was required to approximate absorptance values for standard paint coatings while only 2300 j/cm^3 corresponded to values for CDP prepared metals.

The model, however, predicts different absorptance curves for each metal thickness whereas the data for various thickness all average to about the same values for each of the two coating preparations. This lack of thickness dependence in the data is not predicted and is not understood. Unfortunately, this melt-through data was all taken at an intensity of 3500 W/cm^2 , and a true curve fit and test of the absorptance versus intensity predictions cannot be made.

2. METAL THICKNESS DEPENDENCE OF ABSORPTANCE

The AFWL data on average absorptance for the penetration of painted metals reported in reference 1 show a moderate metal thickness dependence of average absorptance for 2024 aluminum, but none for 6Al4V titanium or 304 stainless steel. Predictions of average absorptance by the paint vaporization model are shown with these data for the three metals in figures 20, 21 and 22.

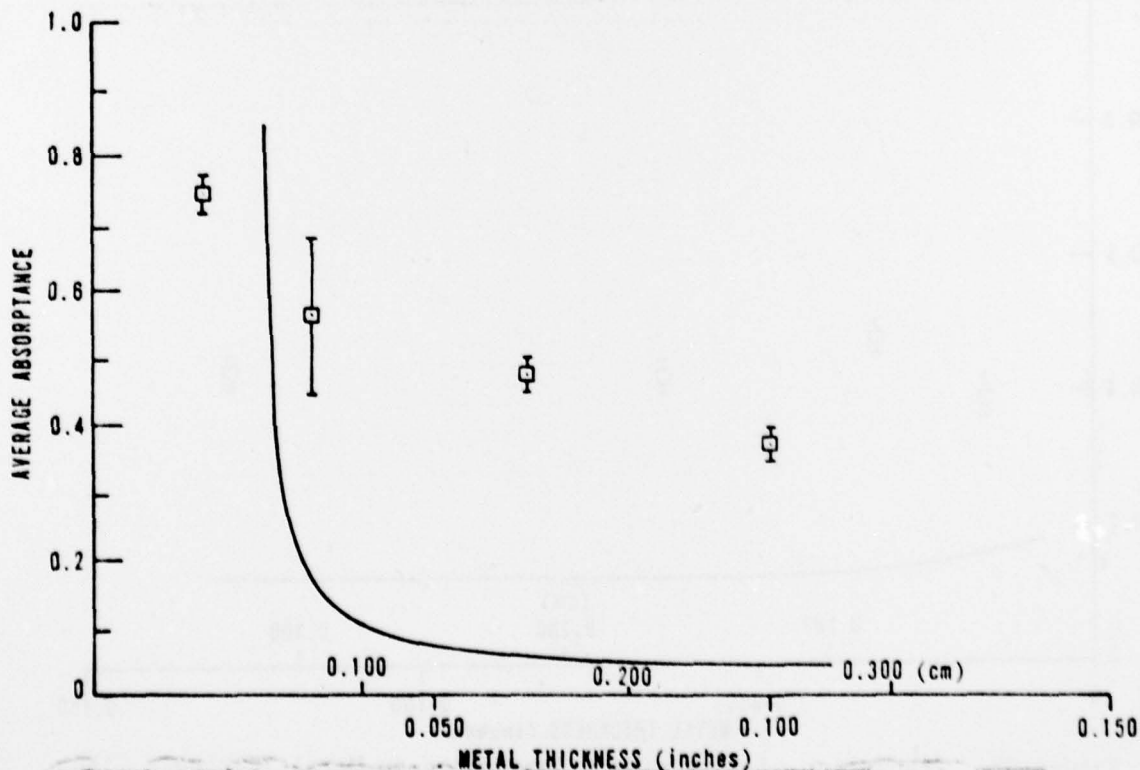


Figure 20. Prediction of Absorptance Dependence on Metal Thickness with AFWL Melt-Through Data: 2024 Aluminum, Painted

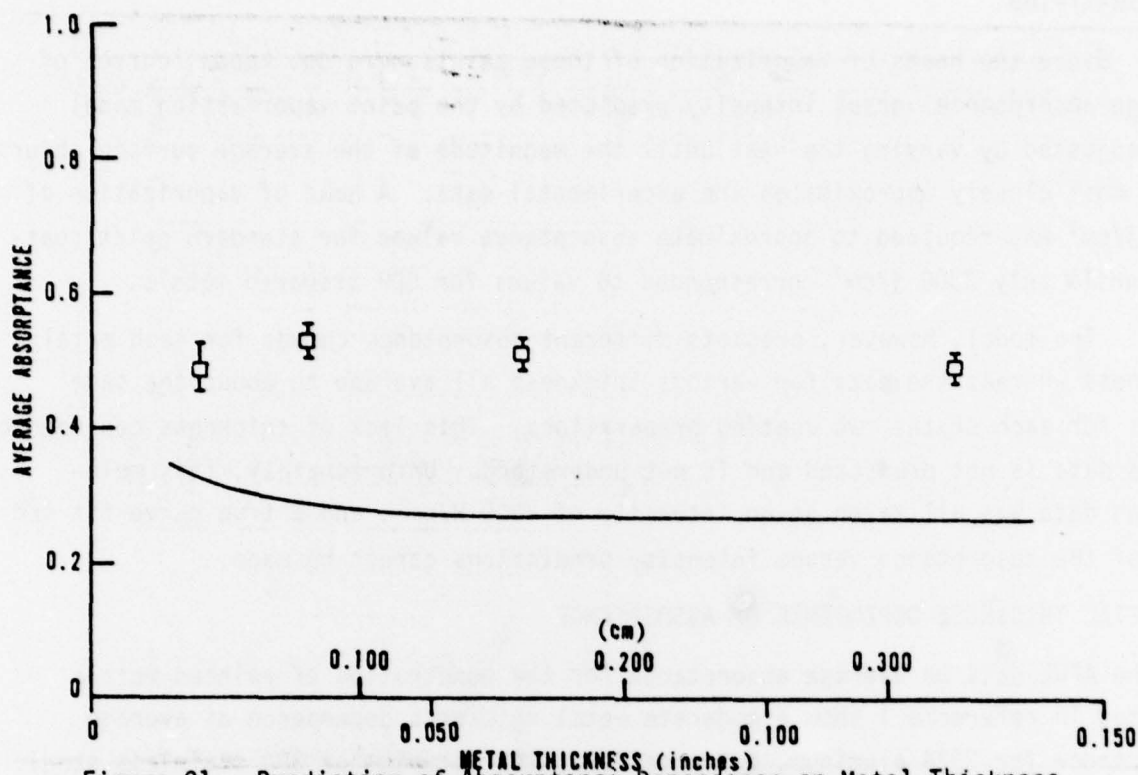


Figure 21. Prediction of Absorbance Dependence on Metal Thickness with AFWL Melt-Through Data: 6A14V Titanium, Painted

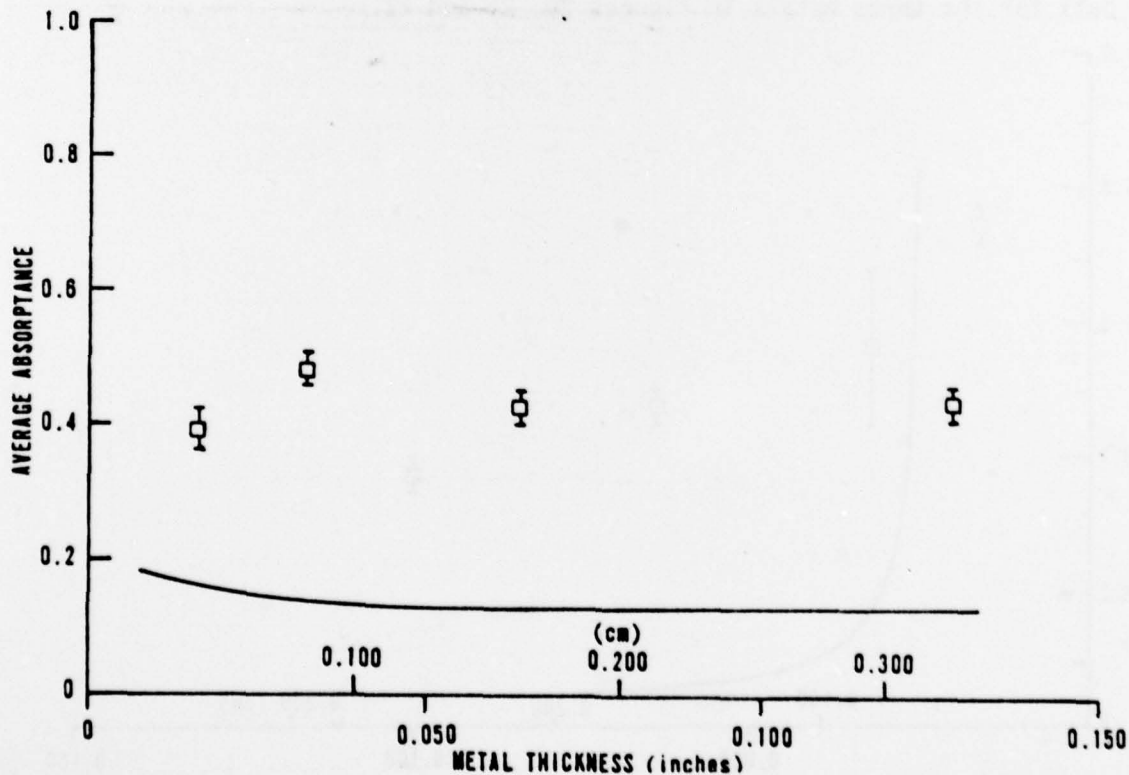


Figure 22. Prediction of Absorbance Dependence on Metal Thickness with AFWL Melt-Through Data: 304 Stainless Steel, Painted

Consistent with the form of the data, little or no thickness dependence is calculated for 304 stainless steel and 6Al4V titanium while a very strong change in average absorptance with changing metal thickness is shown for 2024 aluminum. Although the predicted absorptance values are generally too small, and the sensitivity to metal thickness too great, the theory does say that some dependence on metal thickness should be observed for the better thermal conducting aluminum alloy, just as determined experimentally.

SECTION V

CONCLUSIONS

The paint removal by vaporization model predicts the intensity at which significant increases in average absorptance should occur with decreasing laser intensity. The magnitudes of the calculated absorptance values, however, do not tend to agree well with those obtained experimentally over the entire broad range of intensities.

The theory also suggests that the magnitude of the change in the absorptance with intensity is highly dependent on the kind of paint or coating applied to the metal surface. The behavior of cleanly degrading polymer coatings versus ordinary paints is explained by differences in the heat and temperature of vaporization of the coating. The model also suggests that this difference in average absorptance between CDP and normally painted metal plates is a strong function of intensity, and that the dramatic difference at 3.5 kW/cm^2 may not be as large at other intensities.

The vaporizing paint model suggests that average absorptance should depend on metal thickness for the better thermal conducting 2024 aluminum alloy. The reported data, however, are mixed with AFWL results showing a small thickness dependence and AFML data showing none.

APPENDIX

MEASUREMENT OF EFFECTIVE HEAT OF VAPORIZATION OF PAINT

The effective heats of vaporization of both grey and clear nitrocellulose lacquer were measured by penetrating thick films of paint with laser radiation at an intensity of 3600 W/cm^2 and recording the times required to vaporize the entire film thickness. The paint samples were prepared by alternately applying and allowing to dry many individual applications of paint until a layer of 0.4 to 0.5 cm in thickness is built up. The thick layer of paint released easily from the *teflon* coated substrate. A transverse airflow of several hundred feet per second was used during the ablation tests to more accurately simulate conditions under which paint would be vaporized from actual targets.

If the ablation rate is assumed to be steady for this thickness of material, an average heat of vaporization $(\rho H_v)_p$ in j/cm^3 of material can be calculated directly from the following heat balance

$$(\rho H_v)_p \ell_p = \alpha_p I t_p$$

where ℓ_p is the paint thickness, α_p is the absorptance of the paint surface (assumed to be 0.80), I is the intensity (3600 W/cm^2) and t_p is the penetration time. Results of the ablation experiments are summarized below

<u>Paint</u>	<u>$(\rho H_v)_p \text{ (j/cm}^3\text{)}$</u>	<u>Average</u>
Grey Nitrocellulose Lacquer	2000	2150
Grey Nitrocellulose Lacquer	2300	
Clear Nitrocellulose Lacquer	1360	1350
Clear Nitrocellulose Lacquer	1340	